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13. ABSTRACT (Maximum 200 words) This report highlights the proceedings of the Special Topic Session on "Life-Cycle Management of Aging Aircraft" that was held as a part of Fatigue 2002 in Stockholm, Sweden, 2-7 June 2002. Fatigue 2002 is the 8th in the series of International Fatigue Congresses, which began in Stockholm in 1981 and are recognized as the pre-eminent world conference in the field of fatigue. This special topics session was organized and co-chaired by Drs. Robert P. Wei and D. Gary Harlow at the invitation of the Conference Organizers. The grant fund was used to provide partial support for Drs. Barlow and Wei (Lehigh), and support for Dr. Matthew Miller (Boeing Commercial Airplane Group) to participate as in invited speakers. Support for Dr. Miller, the key (lead off) speaker in the session, was necessitated by the financial constraints imposed at Boeing as a result of the business downturn following September 11, 2001. The other speakers in the session have travel support. In recognition of the importance of this topic and its implication in the design of other engineered systems, Drs. Wei and Harlow were also invited to present a paper on "Aging Aircraft and Life-Cycle Engineering and Management of Engineered Systems" in the Plenary Sessions of the Congress. The principal goals of this session are (i) to provide a perspective overview of the aging aircraft problems, (ii) to assess the Current slate of understanding of the damage mechanisms and of the approaches for fleet management and design, and (iii) to locus on the need for a transformation in the approaches to design and fleet management. Aging aircraft issues have come to the fore because civil and military aircraft are being kept in service for much longer times than contemplated for their original design service objectives (DSO).			
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This report highlights the proceedings of the Special Topic Session on "Life-Cycle Management of Aging Aircraft" that was held as a part of Fatigue 2002 in Stockholm, Sweden, 2-7 June 2002. Fatigue 2002 is the 8<sup>th</sup> in the series of International Fatigue Congresses, which began in Stockholm in 1981 and are recognized as the pre-eminent world conference in the field of fatigue. This special topics session was organized and co-chaired by Drs. Robert P. Wei and D. Gary Harlow at the invitation of the Conference Organizers. The grant fund was used to provide partial support for Drs. Harlow and Wei (Lehigh), and support for Dr. Matthew Miller (Boeing Commercial Airplane Group) to participate as invited speakers. Support for Dr. Miller, the key (lead off) speaker in the session, was necessitated by the financial constraints imposed at Boeing as a result of the business downturn following September 11, 2001. The other speakers in the session have travel support. In recognition of the importance of this topic and its implication in the design of other engineered systems, Drs. Wei and Harlow were also invited to present a paper on "Aging Aircraft and Life-Cycle Engineering and Management of Engineered Systems" in the Plenary Sessions of the Congress.

The principal goals of this session are (i) to provide a perspective overview of the aging aircraft problems, (ii) to assess the current state of understanding of the damage mechanisms and of the approaches for fleet management and design, and (iii) to focus on the need for a transformation in the approaches to design and fleet management. Aging aircraft issues have come to the fore because civil and military aircraft are being kept in service for much longer times than contemplated for their original design service objectives (DSO).

The session was organized as follows:

“Corrosion and Fatigue in Commercial Jet Transport”, Dr. Matthew Miller, Structures and Technology Standards, Boeing Commercial Airplane Group

“Evolution of Corrosion and Corrosion Fatigue in Aircraft Lap Joints”, Dr. Jerzy P. Komorowski et al., Structures, Materials and Propulsion Laboratory, Institute for Aerospace Research, National Research Council Canada

“Fatigue Damage Evolution from Corrosion”, Dr. Graham Clark, Materials Technologies for Through-Life Support, Air Platforms Division, Military Platforms Laboratory, Australian Defence Science and Technology Organisation

“Mechanistically Based Probability Modeling and Reliability Analysis”, Drs. D. Gary Harlow and Robert P. Wei, Mechanical Engineering and Mechanics, Lehigh University

“Nondestructive Inspection and Its Role in Life Cycle Management of Ageing Aircraft”, Dr. David S. Forsyth and Abbas Fahr, Institute for Aerospace Research, National Research Council Canada, and Dr. Floyd W. Spencer, Sandia National Laboratories

“Management of Aging Civil Aircraft – The Challenge of the Aerospace Industry”, Dr. Hans-Juergen Schmidt, Metal Design Principles, and Dr. Bianka Schmidt-Brandecker, Metal Design Principles – Technologies/Materials, AIRBUS

It juxtaposed contributions by principals from the world's leading producers of civil transport aircraft, Dr. Miller from Boeing and Dr. Schmidt from Airbus. The civil aviation side was contrasted against the military side with presentations by Dr. Komorowski from NRC Canada and Dr. Clark from Australian DSTO. Dr. Komorowski's presentation reflected, in part, the USAF concern with lap-splice corrosion. Dr. Forsyth, Canadian NRC, presented a state-of-the-art assessment of NDI; the paper was co-authored by Dr. Spencer of SNL and covered much of the work supported by the FAA. The paper by Dr. Harlow, Lehigh University, highlighted the need for a mechanistically based probability approach, and demonstrated the feasibility and efficacy of such an approach. Abstracts of the presentations are attached. Technical papers reflecting these presentations will be published as a part of the Proceedings of Fatigue 2002.

The essential message from the session is that the impact of corrosion on structural integrity and durability (*i.e.*, safety of flight and continued airworthiness) is now recognized and acknowledged. Boeing, being the early producer of jet transport aircraft, has the largest number of aircraft that remain in service beyond their original DSO. The earliest models Airbus aircraft, on the other hand, are beginning to reach and exceed their original DSO. Many of the aircraft in the air force inventory around the world have also exceeded their DSO. In recognition of the corrosion issue, the approach to the maintenance of civil and military aircraft structures has shifted to the aggressive use of the CPC (corrosion prevention and control) from the find-and-fix, approach. Some modeling efforts are underway to “predict” the evolution of damage from existing damage (*e.g.*, in fuselage lap slices) that are uncovered by nondestructive or tear-down inspection using fracture mechanics. The sensitivity of NDI methodology is insufficient to

provide reliable, quantitative estimates of hidden damage. Overall, the current approaches are largely deterministic and experientially based, and do not address, by and large, the interactive effects of different damage mechanisms (*e.g.*, localized corrosion as a precursor to fatigue damage). As such, they do not lend themselves readily to the optimization of life-cycle design and management in terms of cost of ownership, and system availability and reliability.

There is consensus on the need and adoption of a new paradigm that would transform the current, largely empirically based statistical methodologies (*e.g.*, for corrosion and fatigue analysis) into one that is science and probability based. Such a transformation for aging aircraft is difficult, given the current regulatory and proprietary constraints. Simple replacement with a better alloy, for example, is made impractical by the need for modification of all existing documents and re-certification. Nonetheless, the development of these methods is essential, and requires close cooperation amongst engineers and scientists in structures, materials and nondestructive inspection (NDI). It is recommended that development and demonstration programs be conducted to showcase the efficacy and value of this approach using selected legacy systems or prototypical systems as working models.

Attachments: Abstracts (7)

## **Corrosion and Fatigue in Commercial Jet Transports**

**Matthew Miller**

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As airplanes age, various types of structural deterioration can result. These include fatigue cracks, corrosion and accidental damage. Maintenance programs have been developed using the guidelines in MSG-3 (Maintenance Steering Group), and are designed to ensure any damage will be discovered and repaired before residual strength falls below regulatory load requirements. The consequences of the different damage forms tend to be evaluated independently when developing these programs. For example, an assessment of the fatigue performance of a structural detail will take into account the effect of water but will not assume pre-existing corrosion pits. The Boeing fleet has been in service longer than originally expected. As a result, there is an increasing risk that different forms of deterioration may interact. Some examples of the various types of damage are shown in this paper. One result of findings in the fleet has led Boeing to migrate from a maintenance program designed to react to the presence of corrosion to one that is designed to prevent it. This includes more aggressive use of corrosion prevention materials during production, and mandatory corrosion prevention and control programs.

## **Evolution of corrosion and corrosion fatigue damage in aircraft lap joints**

Jerzy P. Komorowski, Nicholas C. Bellinger and Craig Brooks\*

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The progress achieved in understanding and modelling of fatigue and fracture in aircraft structures has led to the development of Damage Tolerance as the framework for ensuring continued airworthiness. Success of Damage Tolerance and Fail-Safe concepts combined with general economic conditions led to the current situation where increasing number of aircraft are operated beyond their original design goal.

When today's ageing aircraft were designed and built most manufacturers made little allowance for corrosion. Corrosion protection was given low priority as the structures were not expected to remain in service typically beyond 20 years. While all elements of the aircraft industry (the operators, certification authorities and manufacturers) recognised that corrosion could have a negative impact on the structural integrity, this impact could not be quantified until recently. Corrosion continued to be viewed as an economic burden since all corrosion found in an aircraft structure had to be "fixed". This maintenance practice usually included removal of the corrosion and when the net section was found to be reduced by typically 10%, the affected part had to be repaired. Often the term "fix" represented the replacement of an expensive component.

The evolution of corrosion and corrosion fatigue in aircraft lap joints will be described based on detailed studies of lap joints removed from service. Models relating the corrosion state to changes in stress will be presented. Pitting, surface topography, pillowing deformation, material thinning and corrosion multi-site damage will be discussed. Significant reductions in crack nucleation lives have been correlated to the concurrent modification of discontinuities due to the evolution of corrosion and corrosion modified stresses as well as fatigue. Tests supporting the modelling efforts carried out at the authors' laboratory and elsewhere will be described.

Recent advances in understanding and quantification the impact of corrosion on structural integrity have demonstrated that corrosion and corrosion fatigue are also a significant safety concern. To alleviate both the safety concern and to reduce the economic burden, the expansion of the Damage Tolerance framework to include corrosion is advocated.

## Fatigue Damage Evolution from Corrosion

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### Abstract:

While structural impact of corrosion may be experienced as a direct loss of static strength in a component or assembly, the influence of corrosion damage on remaining fatigue life is a significant concern, particularly in configurations which exhibit limited damage tolerance. Recent work has demonstrated that in many cases, simple geometric representations of the damage may be used with some success in fatigue crack growth models to predict remaining life, and indeed such predictions are being evaluated in full-scale test articles containing damage induced to represent service condition. However, several factors complicate the global picture. Firstly, the growth of very small cracks from initial damage is sensitive to the damage geometry, and for many configurations, a confident approach to representing the damage has not yet been demonstrated. Secondly, the effect of material parameters on the initial damage can be very significant; corrosion damage in some aerospace aluminium alloys, for example can involve quite different geometries, leading to unacceptable levels of scatter in the life predictions. Thirdly, local fatigue crack growth behaviour from initial damage of any kind is variable as a result of local microstructure, presumably operating both directly through slip-control or constituent particle control of crack direction and indirectly through crack closure mechanisms with a strain history component. This leads to the observation of upper bounds for crack growth development, accompanied by a wide distribution of non-dominant cracks growing more slowly. Some forms of corrosion damage can display configurations such as crack tip location at grain boundaries which further limit the use of continuum mechanics. Finally, corrosion damage represents only one of a variety of damage states which need to be considered in any fatigue life prediction process; both this, and the variabilities associated with small crack growth and with corrosion damage geometry, make the use of probabilistic models essential in assessing remaining fatigue life. Simple approaches based on empirical data may provide sufficient discrimination to allow the engineer to identify the relative importance of the different damage states. This paper aims to discuss these points in more detail, providing examples, and will highlight the areas where current modelling works well, as well as those areas needing further understanding.

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**MECHANISTICALLY BASED PROBABILITY MODELING  
AND RELIABILITY ANALYSIS\***

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**ABSTRACT**

Corrosion and corrosion fatigue are primary damage mechanisms that affect the reliability and life-cycle management of aircraft. Most of the current methods for fatigue design utilize empirically based statistical analyses and do not explicitly incorporate the effects of corrosion. The main shortcoming of these methods is that the estimated variability is a composite of variations in the controlled external variables, unknown contributions from internal variables, and scatter from measurement error. Accurate reliability analyses, on the other hand, mandate the use of models that capture the critical response to the external as well as internal variables, and that minimize or eliminate the effect of measurement errors. To wit, the need is for mechanistically based probability modeling of the relevant processes of damage evolution. This paper describes the mechanistically based probability modeling approach, contrasts it with the empirically based statistical approaches, illustrates the processes of modeling, and demonstrates its efficacy and merit with an example.

A simplified mechanistically based probability model pitting corrosion and corrosion fatigue in aluminum alloys is selected. The model has been developed from fundamental principles and essential laboratory data. Its validation, however, is dependent on long-term data obtained under normal operating conditions. Four sets of data from tear-down inspections have been provided: two B707 aircraft that had been in commercial service for about 24 and 30 years and two AT-38B aircraft that had over 4,000 flight hours. Using the simplified mechanistically based probability model time-dependent predictions for the extent of damage is compared to the tear-down data. The predicted probability of occurrence from the simple mechanistically based model and the tear-down data are in remarkable agreement. Thus, the efficacy and validity of the approach and its relevancy to airworthiness assessment and fleet life management are demonstrated.

\* This research was supported in part by the Air Force Office of Scientific Research under Grants F49620-98-1-0198 and by ALCOA.

## Nondestructive Inspection and its Role in Life Cycle Management of Ageing Aircraft

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In this paper, the typical structural problems and nondestructive inspection (NDI) requirements associated with the operation of ageing aircraft are reviewed. These include fatigue cracks, corrosion, the interaction of fatigue and corrosion, as well as multisite damage and widespread fatigue damage.

The role of NDI in life cycle management is then discussed. The use of NDI is very different in "safe life" life cycle management than it is in retirement for cause (RFC) or damage tolerance (DT) -based life cycle management. As aircraft reach or surpass their design service objective (DSO), life cycle management may change from safe life to RFC or DT. This places new requirements on NDI.

If NDI is used to ensure the safety of a component, the reliability of NDI must be characterised in order to determine risk. Inspections can then be scheduled to achieve a desired level of risk. Structural analysis will dictate the critical flaw type and location, whether it be a fatigue crack starting in a fillet radius or an amount of section loss due to corrosion. The reliability is then typically measured by estimating the probability of detection of the flaw of interest as a function of the critical flaw dimension deduced from the structural analysis.

Methodologies for determination of POD have been developed in the aircraft engine community, where the critical flaw is usually a fatigue crack characterised by a one dimensional measurement such as length or width. These methodologies also apply to the maintenance of airframes in cases where fatigue cracks are the critical flaw. Recent work by the Federal Aviation Agency (FAA) of the United States and other organisations has resulted in methods for assessing POD for the detection of corrosion damage as well. These new methods and examples of their application will be reviewed.

## **Management of Aging Civil Aircraft – The Challenge of the Aerospace Industry**

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### **Abstract**

Life cycle management of aging aircraft is an essential topic for OEM's (Original Equipment Manufacturers), Operators and STC (Supplemental Type Certification) holders. Extensive efforts are undertaken by all parties to guarantee the airworthiness of airplanes operating close to and beyond their DSG (design service goal). Various groups have been formed under the umbrella of the ARAC (Aviation Regulatory Advisory Committee). These groups comprise of regulators, industry and operators and were tasked to develop rules and processes to maintain the airworthiness of the aging fleet. The major topics were fatigue behavior, widespread fatigue damage evaluation, corrosion aspects, maintenance programs, repairs etc.

This paper describes briefly the major rules and processes mentioned above including the accountabilities of the different parties. Based on the life extension program developed for the Airbus A300 and A300-600 aircraft, the major activities of the OEM's to comply with the newest regulations are explained. This includes methodologies and procedures to analyze structures susceptible to local damage, multiple local damage and multiple site / multiple element damage for the original structure and structural repairs. In addition, the evaluation of other damage types such as corrosion and accidental damages are also described. Furthermore the long term behavior of monolithic aluminum is discussed with respect to material properties and corrosion resistance.

The capability of NDI (nondestructive inspections) techniques is reviewed for specific applications to define the current status and the industrial needs. Special emphasis is given to the structural areas potentially susceptible to widespread fatigue damage (WFD). Guidelines for application of PoD (probability of detection) curves to determine inspection requirements for WFD areas are also presented.

Procedures are described to develop maintenance programs for the aging fleet. This covers all aspects influencing the airworthiness of the aging structure including actions to allow time limited continuation of operation for late assessment of structure. In addition, attention is paid to the specific issue for STC holders who have to cover structural alterations not validated by major structural tests. Finally the statistical evaluation of in-service results is discussed to define appropriate maintenance actions.

Abstract of invited keynote/overview paper prepared for Fatigue 2002, Stockholm, Sweden, June 2-7, 2002

## Aging Aircraft and Life-Cycle Engineering and Management of Engineered Systems\*

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Among the key lessons that have come from research on aging aircraft over the past decade is the recognition that the methodologies for the design of engineered systems needs to be much more holistic and better integrated to meet the challenges of a globally competitive market. To meet these challenges, new methods for design must be developed and be integrated into a new paradigm through which optimization of life-cycle cost can be effected, in consonance with performance objectives and societal responsibilities. The methods must be capable of making reliable predictions of the evolution and probabilistic (*vis-à-vis* statistical) distribution of damage with time. They must capture the influences of key external and internal variables on damage evolution through their interactions with the material's microstructure. Such methods are not currently in place.

The objective of this paper is to challenge the fatigue community to take the lead in developing such methods fatigue analysis, for use in the life-cycle design and management of engineered systems. To this end, a mechanistically based probability (*versus* an experientially/parametrically based statistical) approach is presented and discussed. Its use is illustrated through considerations of corrosion and corrosion fatigue in aluminum alloys in the context of aging aircraft. Its efficacy is demonstrated through a comparison between predicted probabilities of occurrence of damage and tear-down inspection data from the lower wing skins of retired transport aircraft.

\* This research was supported in part by the Air Force Office of Scientific Research under Grants F49620-98-1-0198 and by ALCOA.

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